Gamma-Ray Absorption Processes at High Redshifts

In chapter 4, we discussed in detail the processes which result in the absorption of cosmic γ-rays. In that chapter, we pointed out that there are three main absorption processes of importance under the conditions in interstellar and intergalactic space: Pair-production interactions of cosmic γ-rays with the universal blackbody radiation field, Compton interactions of cosmic γ-rays with electrons in the interstellar or intergalactic gas, and pair-production interactions of cosmic γ-rays with atoms of the interstellar or intergalactic gas. In this chapter, we will show how the effectiveness of these absorption processes is enhanced at high redshifts due to increased photon and matter densities at these redshifts when the universe was in a more compact state. We will also derive the energy dependences of these absorption processes, taking cosmological factors into account as discussed in chapter 9.

13-1 ABSORPTION BY PAIR-PRODUCTION WITH PHOTONS OF THE UNIVERSAL RADIATION FIELD

We begin our discussion by considering the absorption of cosmic γ-rays by pair-production interactions with photons of the universal blackbody radiation field. These interactions are primarily of the form

$$\gamma + \gamma \rightarrow e^+ + e^- \tag{13-1}$$

Detailed calculations of the γ-ray absorption coefficient $\kappa_{\gamma\gamma}(E_\gamma)$ for this process have been made by Gould and Schréder (1967a, b) and have been discussed in chapter 4. This absorption coefficient, which represents the probability per unit pathlength l that a γ-ray will be destroyed by the pair-production process (13-1) can be expressed for γ-rays interacting with a blackbody radiation field of temperature T as

$$\kappa_{\gamma\gamma}(E_\gamma) \simeq \frac{\alpha^2}{2\pi^{1/2}\Lambda}\left(\frac{kT}{mc^2}\right)^3 e^{-\nu}\nu^{1/2} \tag{13-2}$$

where

$$\nu \equiv \frac{(mc^2)^2}{kTE_\gamma} \gg 1 \tag{13-3}$$

$\alpha \simeq 1/137$ being the fine structure constant ($e^2/\hbar c$), $\Lambda = \hbar/mc = 3.86\times10^{-11}$ cm, and k being the Boltzmann constant.

In the other extreme,

$$\kappa_{\gamma\gamma}(E_\gamma) \simeq \frac{\pi\alpha^2}{3\Lambda}\left(\frac{kT}{mc^2}\right)^3 \nu \ln\left(\frac{0.117}{\nu}\right) \qquad \nu \ll 1 \tag{13-4}$$

For cosmological applications, we must take into account the redshift dependences of T and E_γ in an expanding universe,

$$T = T_0(1+z)$$

and (13-5)

$$E_\gamma = E_{\gamma 0}(1+z)$$

where the subscript zero refers to presently observed ($z=0$) quantities, so that $T_0 = 2.7$ K.

Taking the z-dependences into account, we then find that equation (13-2) is applicable in the energy range

$$E_\gamma \ll \frac{1.12\times10^6 \text{ GeV}}{(1+z)^2} \tag{13-6}$$

The optical depth of the universe to γ-rays is then given by

$$\tau(E_\gamma, z_{\max}) = \int_0^{l_{\max}(z_{\max})} dl\ \kappa_{\gamma\gamma}(E_\gamma, z)$$

$$= \int^{z_{\max}} dz\ \kappa_{\gamma\gamma}(E_\gamma, z)\left(\frac{dl}{dz}\right) \tag{13-7}$$

where, from equations (9-41) and (9-42),

$$\frac{dl}{dz} = \frac{10^{28} \text{ cm}}{(1+z)^2(1+10^5 n_0 z)} \tag{13-8}$$

n_0 being the present mean atomic density of all the matter in the universe. We will consider here two types of model universes: a "flat" or Einstein-de Sitter model with $n_0 = 10^{-5}$ cm^3 and an "open" model with $n_0 \ll 10^{-5} z$.

For the flat model, equation (13–7) reduces to

$$\tau(E_{\gamma 0}, z_{\max}) = 3.9 \times 10^8 E_{\gamma 0}^{-1/2} \int_0^{z_{\max}} dz \exp\left[\frac{-1.12 \times 10^6}{(1+z)^2 E_{\gamma 0}}\right] (1+z)^{-1/2} \tag{13–9}$$

with $E_{\gamma 0}$ in GeV.

For $z_{\max} \gg 1$, equation (13–9) can be further simplified to yield

$$\tau(E_{\gamma 0}, z_{\max}) \simeq 1.7 \times 10^2 E_{\gamma 0}^{1/2} (1+z_{\max})^{1/2} \exp\left[\frac{-1.12 \times 10^6}{(1+z_{\max})^2 E_{\gamma 0}}\right] \tag{13–10}$$

A numerical solution found by setting equation (13–7) for $\tau(E_{\gamma 0}, z_{\text{crit}}) = 1$, which defines the critical redshift where the universe becomes opaque to γ-rays of energy $E_{\gamma 0}$, can be well approximated by the expression

$$1 + z_{\text{crit}} \simeq 2.60 \times 10^2 E_{\gamma 0}^{-0.484} \tag{13–11}$$

For the open model, we find

$$\tau(E_{\gamma 0}, z_{\max}) = 3.9 \times 10^8 E_{\gamma 0}^{-1/2} \int_0^{z_{\max}} dz \exp\left[-\frac{1.12 \times 10^6}{(1+z)^2 E_{\gamma 0}}\right] \tag{13–12}$$

For $z_{\max} \gg 1$, equation (13–12) may be approximated by

$$\tau(E_{\gamma 0}, z_{\max}) \simeq 1.7 \times 10^2 E_{\gamma 0}^{1/2} (1+z_{\max}) \exp\left[-\frac{1.12 \times 10^6}{(1+z_{\max})^2 E_{\gamma 0}}\right] \tag{13–13}$$

Thus, there is no significant difference between the opacities of the open and flat model universes. This being the case, we may invert equation (13–11) to obtain an expression for the predicted cutoff energy E_c above which γ-rays originating at a redshift $z_{\max}$ cannot reach us. This relation is then given by

$$E_c \simeq \left(\frac{2.60 \times 10^2}{1+z_{\max}}\right)^{2.06} \tag{13–14}$$

and is graphed in figure 13–1.

In the other extreme, $\nu \ll 1$, we find that as we consider higher and higher energies, the universe will not become transparent to γ-rays again until we reach an energy E_{tr}, where the optical depth $\tau(E_{\text{tr}}, z_{\max})$ again falls to unity. The expression for the optical depth when $\nu \ll 1$ is given

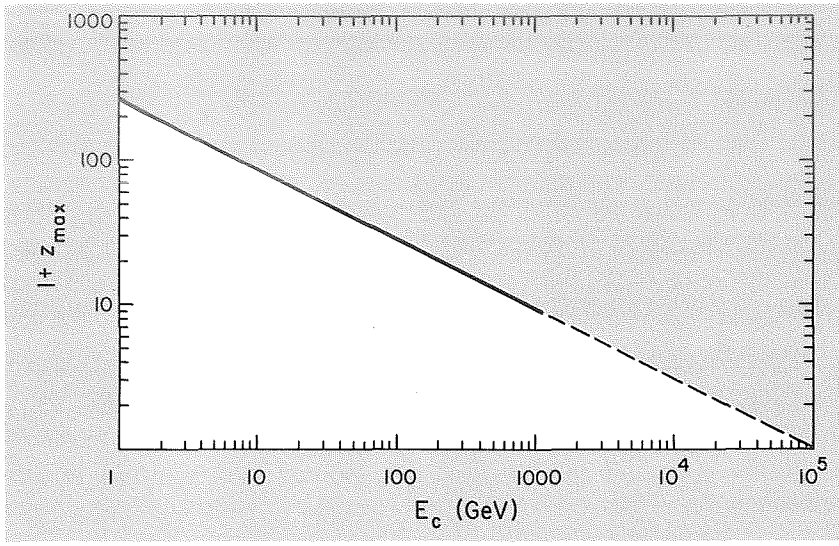

FIGURE 13–1.—Cutoff energy versus redshift for cosmological γ-rays (Fazio and Stecker, 1970)

for a flat universe by

$$\tau(E_{\gamma 0}, z_{\max}) \simeq 4.4\times 10^{13} E_{\gamma 0}^{-1} \int_0^{z_{\max}} dz(1+z)^{-3/2}$$
$$\simeq 8.8\times 10^{13} E_{\gamma 0}^{-1} \qquad (z_{\max} \gg 1) \qquad (13\text{–}15)$$

and for an open universe by

$$\tau(E_{\gamma 0}, z_{\max}) \simeq 4.4\times 10^{13} E_{\gamma 0}^{-1} \int_0^{z_{\max}} dz(1+z)^{-1} \simeq 4.4\times 10^{13} E_{\gamma 0}^{-1} \ln(1+z_{\max}) \qquad (13\text{–}16)$$

In both cases we find that $E_{\rm tr} > 10^{13}$ GeV so that we may safely assume that the universe, due to the blackbody radiation field, is essentially opaque to γ-rays of all energies greater than E_c.

13–2 GAMMA-RAY ABSORPTION BY PAIR-PRODUCTION AND COMPTON INTERACTIONS WITH INTERGALACTIC GAS

Gamma-ray absorption by pair-production and Compton interactions with intergalactic gas at high redshifts has been examined by Rees (1969a, b) and by Arons and McCray (1969). Our discussion here essentially follows theirs. The absorption cross section for Compton interac-

tions is given in equations (4–19) and (4–20); that for pair-production, in equation (4–23). These absorption processes are discussed in chapter 4, and the cross sections are graphed in figure 4–2. The total absorption cross section above 100-MeV energy is roughly constant and equals 1.8×10^{-26} cm^2. For the case of a constant absorption cross section, the optical depth as a function of redshift $z_{\max}$ is given by equations (13–7) and (13–8) as

$$\tau(z_{\max}) = \int_0^{z_{\max}} dz\, n(z)\sigma \left(\frac{dl}{dz}\right)$$

$$= n_0 \sigma c H_0^{-1} \int_0^{z_{\max}} \frac{(1+z)}{(1+\Omega z)^{1/2}}$$

$$= \frac{2}{3}\tau_c \Omega \left[\left(3+z-\frac{2}{\Omega}\right)(1+\Omega z)^{1/2} - \left(3-\frac{2}{\Omega}\right) \right] \qquad (13\text{–}17)$$

where

$$\tau_c \equiv n_c \sigma c H_0^{-1} = 1.8 \times 10^{-3} \qquad (13\text{–}18)$$

a result which was first obtained by Gunn and Peterson (1965).

For an Einstein-de Sitter universe ($\Omega = 1$)

$$\tau(z_{\max}) = \frac{2}{3}\tau_c [(1+z_{\max})^{3/2} - 1] \qquad (13\text{–}19)$$

and for a low-density universe ($\Omega z \ll 1$)

$$\tau(z_{\max}) = \frac{\Omega}{2}\tau_c [(1+z_{\max})^2 - 1] \qquad (13\text{–}20)$$